PRODUCTION OF LITHIUM, BERYLLIUM, AND BORON BY HYPERNOVAE

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ABSTRACT

We investigate a possible nucleosynthetic signature of highly energetic explosions of C-O cores ("hypernovae," HNe) which might be associated with gamma-ray bursts (GRBs). We note that the direct impact of C- and O-enriched hypernova ejecta on the ambient hydrogen and helium leads to spallation reactions which can produce large amounts of the light nuclides lithium, beryllium, and boron (LiBeB). Using analytic velocity spectra of the hypernova ejecta, we calculate the LiBeB yields of different exploding C-O cores associated with observed hypernovae. The deduced yields are $\sim 10^3$ times higher than those produced by similar (direct) means in normal Type II supernovae, and are higher than the commonly used ones arising from shock wave acceleration induced by Type II supernova (SN) explosions. To avoid overproduction of these elements in our Galaxy, hypernovae should be rare events, with $\lesssim 10^{-3}$ hypernova per supernova, assuming a constant HN/SN ratio over time. This rate is in good agreement with that of long duration GRBs if we assume that the gamma-ray emission is focussed with a beaming factor $\Omega/4\pi \lesssim 10^{-2}$. This encouraging result supports the possible HN–GRB association. Thus, Galactic LiBeB abundance measurements offer a promising way to probe the HN rate history and the possible HN-GRB correlation. On the other hand, if hypernovae are associated to very massive pregalactic stars (Population III) they would produce a LiBeB pre-enrichment in proto-galactic gas, which could show up as a plateau in the lowest metallicities of the Be-Fe relation in halo stars.

Subject headings: cosmic rays — nuclei, nucleosynthesis, abundances — supernovae — gamma-ray bursts

1. Introduction

An unusual class of very energetic supernovae ("hypernovae," hereafter HNe) has recently been observed (Iwamoto et al. 1998, 2000). Observationally, these events are identified by their high luminosities and peculiar light curves. Theoretically, these events seem to be the highly energetic core collapse explosion of C-O cores (Iwamoto et al. 1998, 2000; Woosley et al. 1999; Nakamura, Mazzali, Nomoto, & Iwamoto 2001; Tan, Matzner, & McKee 2001). It has been suggested (Iwamoto et al. 1998; Wheeler, Yi, Höflich, & Wang 2000) that these may be associated with at least some gamma-ray bursts (GRBs).

The purpose of this paper is to point out that these very energetic stellar explosions are good sites for the copious production of the light elements lithium, beryllium, and boron (LiBeB). This occurs through the collision of the HN ejecta with the circumstellar medium. Fields et al. (1996) noted that such nucleosynthesis occurs in the explosion of all supernova (hereafter SN) ejecta, when the fastest ejecta collide with the surrounding medium and undergo spallation reactions. Fields et al. found the LiBeB production is particularly large for exploding C-O cores (resulting from, e.g., WR explosions or binary interactions). Even so, for explosions of C-O cores with "normal" energies, the net light element yields are too small to significantly affect the Galactic evolution of LiBeB.

As we will see, for hypernovae the LiBeB production efficiency is much higher, due to: (1) a surface composition of hypernovae which is essentially composed of C and O, ideal parent objects for spallation into lighter isotopes; and (2) a significant fraction of the outer envelope is propelled to high velocities (energies higher than nuclear reaction threshold) due to the very high kinetic energy released in their explosion. For the case of hypernovae, the astrophysical context is reasonably well-defined because there are only two key physical parameters (explosion energy, ejected mass), both of which are constrained by observations of the supernova light curves. Adopting a calculated velocity (energy) spectrum of the ejected C and O it is straightforward to evaluate the absolute yield of light elements by spallation. The only difficulty is that the fast nuclei are slowed down in the course of their propagation, and that the cross sections are energy dependent. The procedure adopted to take into account these effect is explained in Fields et al. (1996).

We combine our theoretical LiBeB yields with a simple model of Be chemical evolution to quantify the hypernova contribution to Galactic Be. By comparing these results with observed Be abundance determinations in very metal poor stars in the halo of our Galaxy, we place an upper limit on the ratio of HNe to Type II SNe. This limit holds assuming a constant HN/SN ratio. In addition, if we assume a correlation between hypernovae and gamma ray bursts, we can constrain the fraction of GRB that can be identified as LiBeB producing hypernovae.

The term “hypernova” has been used in different ways by different authors (e.g., Paczyński 1998; Iwamoto et al. 1998, 2000), so it is important to clarify the meaning used here. We define a hypernova as a core-collapse explosion whose detailed mechanism is unknown, whose kinetic energy is much higher than usual, and whose envelope is dominated by carbon and oxygen (rather than hydrogen and helium). Such events are possibly associated with long-timescale GRBs, and we will discuss this possible association in detail in §4.

Table 1: Parameters of Hypernova Candidates

Object	$M(\mathrm{C-O})$ $M_\odot$	$M_{\rm ej}$ $M_\odot$	$E_{\rm K}$ 10^{51} erg	$v_* = (E_{\rm K}/M_{\rm ej})^{1/2}$ 10^4 km/s	Reference
SN1994I*	2.1	0.9	1	0.75	Nomoto et al. (1994)
SN1994I($\times$10)	2.1	0.9	10	2.4	
SN1994I($\times$30)	2.1	0.9	30	4.1	
SN1997ef	10	7.6	8	0.73	Iwamoto et al. (2000)
SN1998bw(a)	13.8	10.8	30	1.2	Iwamoto et al. (1998)
SN1998bw(b)	6	4.6	22	1.5	Woosley et al. (1999)
SNIa	1.4	1.4	1	0.60	

* The reference model of Fields et al. (1996).

2. Production of LiBeB by Different Stellar Progenitors

We now compute the production of LiBeB by hypernovae. As seen in Table 1, the bulk properties of HNe are diverse. In particular, the explosion energies and ejected masses apparently span a considerable range. One would expect that the LiBeB yields are very sensitive to both of these parameters. We will show this to be the case, and we will use analytic expressions to derive the scaling of the yields with these parameters.

Fields et al. (1996) noted that the fastest ejecta of a supernova explosion have energies above the thresholds for nuclear spallation reactions. When these fast particles interact with the surrounding medium, they will therefore produce LiBeB. The light element production depends on the velocity spectrum of the explosion, particularly that of the outermost layers. The LiBeB yields also scale as the local ISM (target) density, while the irradiation timescale is that of the ionization energy losses and thus scale inversely with density. These density effects cancel, giving a LiBeB nucleosynthesis which is independent of the local density but which does depend on the fast particle (and ISM) composition. The Fields et al. (1996) study is based on the numerical simulation of the Type Ic event SN 1994I (Nomoto et al. 1994), which is modeled as the explosion of a 2.1 $M_\odot$ C-O core. In this model the outermost and fasterst layers (the only ones that count in our problem) are a mixture of C and O with no H and a small ($\sim 10\%$) admixture of He.

The velocity spectrum of the outermost layers can be calculated analytically, as was shown by

Imshennik & Nadyozhin (1988, 1989) and reviewed in Nadyozhin (1994); these results have recently been confirmed and extended into the relativistic regime by Matzner & McKee (1999). Fields et al. (1996) give a full derivation of the relevant formulae for our problem; here, we will only summarize key inputs and results. The particle spectrum is determined by the bulk hydrodynamics of the problem, namely the velocity (or kinetic energy) distribution as a function of mass shell $M(>v)$. The ejected particles have a energy spectrum $dN/d\varepsilon = m^{-2}\ v^{-1}\ dM/dv$ where m is the mean particle mass. Nadyozhin (1994) and Matzner & McKee (1990) find that the velocity spectrum of the fastest ejecta is a power law

$$M(>v) = \zeta^s\ M_{\rm ej}\,(v/v_*)^{-s} \tag{1}$$

where $M_{\rm ej}$ is the ejected mass and $v_* \equiv (E/M_{\rm ej})^{1/2}$ is a characteristic speed associated with the ejecta of an explosion having energy E. The constants ζ and s take on different values depending on the polytropic index relevant to the problem; for our case of $n = 3$, we have $\zeta = 1.92$ and $s = 7.2$. Eq. (1) holds for the fastest, outermost ejecta, i.e., for $M(>v) \ll M_{\rm ej}$.

Table 2: LiBeB Yields for Hypernova Candidates

Object	LiBeB Yield $\langle m_{{\rm ej},i}\rangle_{\rm HN}$ $(M_\odot)$ ^{6}Li	^{7}Li	^{9}Be	^{10}B	^{11}B
SN1994I	0.13E-06	0.32E-06	0.40E-07	0.26E-06	0.12E-05
SN1994I(×10)	0.50E-03	0.13E-02	0.16E-03	0.10E-02	0.46E-02
SN1994I(×30)	0.26E-01	0.65E-01	0.83E-02	0.54E-01	0.24E+00
SN1997ef	0.88E-06	0.22E-05	0.28E-06	0.18E-05	0.81E-05
SN1998bw(a)	0.41E-04	0.10E-03	0.13E-04	0.84E-04	0.38E-03
SN1998bw(b)	0.12E-03	0.31E-03	0.39E-04	0.25E-03	0.11E-02
SNIa	0.40E-07	0.10E-06	0.13E-07	0.82E-07	0.37E-06

The key points here are that (1) the particles follow a steep power law spectrum in kinetic energy per nucleon ε, with $dN/d\varepsilon \propto \varepsilon^{-(s+1)/2} = \varepsilon^{-4.1}$ and (2) the fraction of ejected particles above a particular velocity (or energy) threshold–and thus the fraction available for LiBeB production spallation reactions–scales as the very strong power $v_*^s = v_*^{7.2}$. Thus, once we adopt the appropriate value of s, the spectrum of particles is fixed, as are the ratios among the LiBeB isotopes produced for a given projectile and target composition. These results are (almost) independent of the explosion energy or ejected mass, and thus should not vary much from one HN to the next.[1] By contrast, the total LiBeB yield, e.g., $\langle m_{\rm ej,Be}\rangle_{\rm HN}$, depends very strongly on the explosion energy and ejected mass, with scaling

$$\langle m_{\rm ej,Be}\rangle_{\rm HN} \propto M_{\rm ej}^{(s-2)/2} E^{s/2} = M_{\rm ej}^{-3.1} E^{3.6} \tag{2}$$

[1]In fact, a dependence does remain since the spectrum of eq. (1) is cut off at an energy $E_{\rm max} \propto v_*^2$. However, this is more difficult to calculate accurately as it depends on the details of shock breakout. Also, for the steeply falling spectra and high energies we consider here, the results are only mildly sensitive to $E_{\rm max}$.

and thus we can expect strong variations in LiBeB yields among HNe.

So if the hypernova energy is a factor of 10 higher than the usual 10^{51} erg, then the mass ejected above LiBeB thresholds – and thus the yields – goes up by a factor of $10^{3.6} = 4000$. This suggests that (low-mass) hypernovae can be prolific LiBeB sources. Given the composition and spectrum of the projectiles and the known composition of the target, one calculates the spallation yield in the thick target approximation (excellent in our problem), taking into account the energy dependent spallation cross sections.

A grid of models, comprising various kinds of exploding C-O cores (observed and not) is presented in Table 2. One can verify that the yields obey the scalings given in eq. (2). The most copious LiBeB producers are obviously those with lower mass and higher kinetic energy. Type Ia SNe are a relatively interesting source due to their frequency, but they are less productive than low mass hypernovae, since they eject comparable masses but have 10 times less energy. The high energy explosions of massive hypernovae is overcompensated by their heaviness. Except for the energy, normal Type Ic SNe are events very similar to the SN 1998bw massive hypernova. The extremely large LiBeB production by low mass HNe, if they exist, makes them the most efficient LiBeB-producing events known. As such they could have played a role in the evolution of light elements in the early Galaxy, and possibly the intergalactic medium if there were Pop III HNe. Note that the calculated B/Be ratio (Table 2), around 30, is consistent with the same ratio observed in stars all along the metallicity scale (Duncan et al. 1997, Primas et al. 2000, Cunha et al. 2001). Moreover the isotopic ratios of lithium (^{7}Li/^{6}Li $\simeq 2.1$) and boron (^{11}B/^{10}B $\simeq 4.1$) are in good agreement with these observations.

3. LiBeB Abundance Constraints on Hypernova Rates

We now turn to the contribution of HNe to the Galactic evolution of LiBeB. From this point of view, it is important to note that HN represent a *primary* LiBeB production mechanism. That is, due to their self-produced C-O cores, the HNe ejecta are always enriched in C and O, and thus the yields of Be are essentially independent of the ambient interstellar medium metallicity. Consequently, we expect a linear scaling between the HN ejecta of Be and O, Be $\propto$ O, and thus a constant Be/O ratio in the Galaxy. Of course, HNe are not the only primary mechanism; another is LiBeB production via metal-rich particles accelerated in superbubbles (Vangioni-Flam et al. 2000). In addition, standard Galactic cosmic rays, with a composition which reflects the ISM metallicity, give a *secondary* contribution which does depend on the interstellar metallicity, and so scales as Be $\propto$ O^2.

The relative contribution of primary and secondary processes to Be nucleosynthesis thus depends on the Be-O relation. Unfortunately, O/H is difficult to measure in cool stars, and controversy has arisen as two different O/H (and O/Fe) trends have been claimed. If O/Fe changes in Pop II (e.g., Israelian *et al.* (1998; 2001); Boesgaard, King, Deliyannis, & Vogt (1999b); Mishenina, Ko-

rotin, Klochkova, & Panchuk (2000)) Fields et al. (2000) showed that both primary and secondary components are needed, with primary dominating at [O/H] $\lesssim -1.5$, and secondary dominating above. On the other hand, if O/Fe is constant in Pop II (e.g., Carretta, Gratton, & Sneden (2000); Fulbright & Kraft (1999)), then a primary source of LiBeB dominates until the roughly solar metallicities (Vangioni-Flam et al. 1998). Thus, *regardless* of the O/Fe behavior, there is a need for primary Be at some level; the quantitative amount does depend on the details of O data. In what follows we will consider the implications of both possibilities for O/Fe.

One can place LiBeB in full chemical evolution context (e.g., Vangioni-Flam et al. 2000; Fields & Olive 1999) but a simplified approach, appropriate for Pop II, allows one to focus on the physics of the HN contribution to Be. In this approximation, we neglect the (small) astration of Be, and thus the primary production of LiBeB species i is described by

$$M_{\rm gas}\frac{\rm d}{{\rm d}t}X_i \simeq \langle m_{{\rm ej},i}\rangle_{\rm HN}\mathcal{R}_{\rm HN} + \langle m_{{\rm ej},i}\rangle_{\rm SN}\mathcal{R}_{\rm SN} \tag{3}$$

where $\langle m_{{\rm ej},i}\rangle_{\rm HN}$ is the mean mass in i created by one HN, and $\langle m_{{\rm ej},i}\rangle_{\rm SN}$ is the same quantity for one (superbubble) SN; the rates of each event are given by $\mathcal{R}_{\rm HN}$ and $\mathcal{R}_{\rm SN}$.

Since we are considering primary production, the yields are independent of the initial ISM metallicity, and in fact eq. (3) applies not only to primary LiBeB but also to metals such as O and Fe. Thus we can write

$$\beta \equiv \frac{X_{\rm Be}}{X_{\rm O}} = \frac{\epsilon_{\rm HN}\langle m_{\rm ej,Be}\rangle_{\rm HN} + \langle m_{\rm ej,Be}\rangle_{\rm SN}}{\langle m_{\rm ej,O}\rangle_{\rm SN} + \epsilon_{\rm HN}\langle m_{\rm ej,O}\rangle_{\rm HN}} \tag{4}$$

where we have assumed a constant ratio

$$\epsilon_{\rm HN} = \mathcal{R}_{\rm HN}/\mathcal{R}_{\rm SN} \tag{5}$$

which we will refer to as the "HN rate parameter."

Given information about spallation and stellar yields, eq. (4) allows us to relate the observed $X_{\rm Be}/X_{\rm O} \simeq 16/9$ Be/O to the hypernova rate parameter $\epsilon_{\rm HN}$:

$$\epsilon_{\rm HN} = \frac{\beta\langle m_{\rm ej,O}\rangle_{\rm SN} - \langle m_{\rm ej,Be}\rangle_{\rm SN}}{\langle m_{\rm ej,Be}\rangle_{\rm HN} - \beta\langle m_{\rm ej,O}\rangle_{\rm HN}} \tag{6}$$

Unfortunately, eq. (6) as it stands is difficult to evaluate due to the model-dependence of the superbubble $\langle m_{\rm ej,Be}\rangle_{\rm SN}$ and the unknown nature of the HN oxygen yield $\langle m_{\rm ej,O}\rangle_{\rm HN}$. We can still make progress, however, by setting an upper limit to $\epsilon_{\rm HN}$, as follows. First, we note that the largest possible oxygen yield is when the ejecta is pure oxygen: $\langle m_{\rm ej,O}\rangle_{\rm HN} \le \langle m_{\rm ej,tot}\rangle_{\rm HN}$. We also note that the HN contribution is maximized when we ignore the SN contribution. It thus follows that we may limit the HN rate parameter to be

$$\begin{aligned}\epsilon_{\rm HN} &\le \frac{\beta\langle m_{\rm ej,O}\rangle_{\rm SN} - \langle m_{\rm ej,Be}\rangle_{\rm SN}}{\langle m_{\rm ej,Be}\rangle_{\rm HN} - \beta\langle m_{\rm ej,tot}\rangle_{\rm HN}} \\ &\le \frac{\beta\langle m_{\rm ej,O}\rangle_{\rm SN}}{\langle m_{\rm ej,Be}\rangle_{\rm HN} - \beta\langle m_{\rm ej,tot}\rangle_{\rm HN}}\end{aligned} \tag{7}$$

With eq. (7) in hand, we can now place limits on the HN rate parameter. We adopt the SN oxygen yield $\langle m_{\rm ej,O}\rangle_{\rm SN} = 2M_\odot$, which is insensitive to the choice of initial mass function. For the total hypernova ejected mass we adopt the large and thus conservative value $\langle m_{\rm ej,tot}\rangle_{\rm HN} = 10M_\odot$. Finally, we must adopt a Be yield for HNe. As Table 2 illustrates, the wide range of HN masses and energies implies a huge range in Be yields, spanning orders of magnitude. We will adopt $\langle m_{\rm ej,Be}\rangle_{\rm HN} \simeq 10^{-5}M_\odot$, the lower of the two values found for SN 1998bw in Table 2. The energy and ejected mass dependence for this value are as in eq. (2).

With these parameters, we can evaluate eq. (7) once we have made a choice of β. As noted above, this depends on the oxygen data. The weaker limit to $\epsilon_{\rm HN}$ comes from the constant O/Fe case, in which Be is primary over all of Pop II. In this case, we have $\beta \sim 3 \times 10^{-8}$, and thus our fiducial numbers give

$$\epsilon_{\rm HN} \leq 6 \times 10^{-3} \tag{8}$$

This evaluation is coherent with the upper limit which can be derived from the beryllium abundance in extremely metal-poor stars, as observed with the VLT by Primas et al. (2000). On the other hand, if O/Fe varies, then the relevant Be/O ratio is that of the primary component, which Fields et al. (2000) showed to be $\beta \sim 8 \times 10^{-10}$. As this is smaller, we get a tighter limit:

$$\epsilon_{\rm HN} \leq 1.6 \times 10^{-4} \tag{9}$$

There are various ways one can physically interpret a limit to $\epsilon_{\rm HN}$. If one attributes the origin of a HN to a mass effect, then $\epsilon_{\rm HN}$ is essentially the fraction (by number) of massive stars which become a HN. If we assume that stars above some lower mass limit $m > m_{\rm HN}$ become a HN, then for a Salpeter mass function (with massive stars in the range $10M_\odot \leq m \leq 100M_\odot$) we derive $m_{\rm HN} > 91M_\odot$ from eq. (8), and $m_{\rm HN} > 99M_\odot$ from eq. (9). These lie at the upper edge of the allowed range, reflecting the smallness of the HN contribution. The HN origin could also be related to additional physical parameters, such as binary interactions or rotation. In this case, the limit to $\epsilon_{\rm HN}$ would reflect not only a mass effect but also the fraction of systems where such conditions are present.

The variation in HN energy and ejected mass will also have an important effect on the limits quoted. Had we adopted weaker explosions, or more massive ejecta, these would lead to lower Be yields and thus weaker limits on $\epsilon_{\rm HN}$. One could even imagine turning the problem around: given an independent measurement of $\epsilon_{\rm HN}$, one could use these limits to infer the mean v_* for HNe.

4. On the Possible Association Between GRBs and Hypernovae

The Burst and Transient Source Experiment (BATSE) on board the Compton Gamma-Ray Observatory (CGRO) detected more than 2500 gamma-ray bursts (hereafter GRBs) from 1991 to 2000. The distribution of these bursts over the sky is highly isotropic but the number of faint bursts is notably smaller than the expected number if the distribution of bursts was homogeneous in a

Euclidean universe (Fishman and Meegan 1995 and references therein). These two facts provide strong evidence that GRBs occur at cosmological distance (Paczyński 1991). This cosmological origin is now firmly established for the long bursts (> 2 s) thanks the discovery of their afterglows made possible by the Beppo-SAX satellite. These late and fading counterparts are first detected in the X-ray range, then in the optical and later in the radio range. About twenty optical afterglows have been discovered to date. The redshifts of most of these events have been measured, and range from $z = 0.433$ (GRB 990712) to $z \simeq 4.5$ (GRB 000131). These values represent either a direct measure of the redshift of the afterglow or in a few cases the redshift of the host galaxy.

The two most popular models for the source of GRBs associate them with the coalescence of two compact objects (NS-NS or NS-BH, Eichler et al. 1989; Paczyński 1991; Narayan et al. 1992; Mochkovitch et al. 1993) or the collapse of a very massive star into a black hole (collapsar, Woosley 1993). Such collapsars could be either the collapse of a single Wolf-Rayet star endowed with rotation, or the merger of the core of a massive star with a black hole or a neutron star, and should lead to hypernovae as defined in this paper. The recent observations of the optical afterglows of long bursts and the observations of their host galaxies provide several pieces of evidence in favor of the association with massive stars: the indication of dust extinction in optical afterglows and gas absorption in X-ray afterglows suggest that GRBs occur near star-forming regions (Paczyński 1998; Bloom et al. 1998). The first direct evidence for the GRB-massive star association comes with the supernova SN 1998bw which is probably associated with GRB 980425 (Galama et al. 1998). GRB 980326 and GRB 970228 might also be associated with supernovae (Bloom et al. 1999; Reichart 1999).

As the sample of long bursts with a determined redshift is still small, the distribution of GRBs as a function of redshift z must be estimated indirectly. This has been done by many authors (for a review, see Piran 1999) who fit the observed peak flux distribution assuming a given rate of bursts $\rho_{\rm GRB}(z)$. The other parameters for such a calculation are the luminosity distribution of bursts $\Phi(L)$, which is usually taken to be independent of z, the assumed spectral shape for the GRBs and the usual cosmological parameters. The burst rate obtained by this method is very uncertain. Whereas the results of these calculations are weakly sensitive to the adopted values of the cosmological parameters (Cohen & Piran 1995), it has been shown that the BATSE sample is not large enough to distinguish between to extreme assumptions : a constant rate

$$\rho_{\rm GRB}(z) = \rho_0 \tag{10}$$

or a rate proportional to the cosmic star formation rate

$$\rho_{\rm GRB}(z) \propto \rho_{\rm SFR} \ . \tag{11}$$

This is true in particular when relaxing the assumption that GRBs are standard candles (Krumholz et al. 1998), which was usually made for the first calculations (Sahu et al. 1997; Wijers et al. 1998) but is not supported by the observations.

In this paper we will only consider the case of long GRBs. As we are interested in putting constraints on the association between GRBs and hypernovae, we will assume that the burst rate is

indeed proportional to the cosmic star formation rate. We will use the results obtained by Porciani & Madau (2001). They did a recent estimation of the GRB rate under this assumption. They used $\Omega_{\rm M} = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 65h_{65}$ km/s/Mpc. The spectral shape of the GRBs was given by the so called GRB-function (Band et al. 1993). This is a phenomenological 4-parameter function which is known to fit very well the observed spectra. They used the following parameters : $\alpha = -1.0$ for the low energy slope, $\beta = -2.25$ for the high energy slope and $E_{\rm b} = 511$ keV for the break energy, which corresponds to the typical values obtained by Preece et al. (2000) who did a detailed spectral study of a large sample of long GRBs. We know from the few GRBs with a measured redshift that the luminosity of GRBs is strongly variable but the luminosity distribution is very poorly constrained. Porciani and Madau used a power-law distribution :

$$\Phi(L) = C\left(\frac{L}{L_0}\right)^\gamma \tag{12}$$

where C is correctly normalized to have $\int_0^{+\infty}\Phi(L)dL = 1$. With all these assumptions and using different estimations of the SFR, they found that their best fits give a GRB rate of about 1-2 bursts per million Type II supernovae, i.e.,

$$\epsilon_{\rm GRB,4\pi} = 1 - 2\times 10^{-6} \tag{13}$$

Clearly, this is much lower than the HN parameter found in the previous section.

However, this does not demand that we reject the possible association between HNe and GRB. If the GRB emission is focussed in an opening angle Ω, the rate parameter in eq. (13) has to be corrected upward by a factor $(\Omega/4\pi)^{-1}$. To reconcile the rates, we require that $\Omega/4\pi \simeq 2\,10^{-4}$–$10^{-2}$. This range has a considerable overlap with observed broad distribution of beaming factor which spans $\Omega/4\pi \sim 10^{-3} - 10^{-1}$ (Frail et al. 2001). Moreover, our estimation of the hypernovae rate $\epsilon_{\rm HN}$ scales with the HN parameters in the same way as the Be yield, i.e., as $M_{\rm ej}(E/M_{\rm ej})^{s/2} = M_{\rm ej}(E/M_{\rm ej})^{3.6}$. This strong dependence means that a modest change in $E/M_{\rm ej}$ produces a large shift in $\Omega/4\pi$. Thus one might hope to turn the problem around, and use an accurate measure of the mean $\Omega/4\pi$ to infer the mean $E/M_{\rm ej}$.

Despite this encouraging result, important uncertainties remain, especially due to our poor knowledge of the explosion mechanism. If only a subclass of GRB progenitors leads to a hypernova as we have defined, then $\epsilon_{\rm HN}$ has to be compared to a fraction only of $\epsilon_{\rm GRB}$ and the constrain on the beaming angle or the $E/M_{\rm ej}$ ratio becomes more severe. On the other hand, the opposite situation cannot be excluded: the isotropic envelope expansion that we associate with a HN is always present, but the GRB is produced only when certain unknown conditions allow the acceleration of an ultrarelativistic outflow. In this case $\epsilon_{\rm HN}$ has now to be compared with $\epsilon_{\rm GRB}$ divided by the fraction of explosions producing a GRB and large beaming angle are allowed, even with the $E/M_{\rm ej}$ ratio that we have adopted here.

5. Conclusion

Motivated by recent theoretical and observational interest in hypernovae, we have considered the LiBeB production by these objects. We find that the LiBeB yields are very sensitive to the explosion energy and ejected mass. If these parameters typically take values as found for SN 1998bw, then the Be yields can be very large due to the high explosion energy.

Using the yields found for SN 1998bw, we have calculated the impact of HNe on LiBeB evolution in the galaxy. HNe represent a primary source of Be, and thus are constrainted by the observed primary component of Be vs O. Using the observed Be data at low metallicities, we are thus able to place limits on the HN/SN ratio. If we further associate HNe with GRBs, we can infer a limit on the beaming angle of the GRB emission $\Omega/4\pi \lesssim 10^{-2}$ which is consistent with independent estimates. This agreement is encouraging, though of course significant uncertainties remain.

Under the simple assumption of a constant HN/SN ratio which has been made to derive these limits, there are potentially important consequences for LiBeB evolution. The Li-Fe relation shows a small slope (Ryan, Norris, & Beers 1999) which is consistent with standard GCR production of Li (Ryan et al. 2000) but within errors also allows room for other primary Li contributions. As the Li-Fe relation is measured more precisely, one may be able to detect or limit the Li production by HNe, in addition to that of standard and superbubble cosmic rays.

The assumption that the HN/SN ratio is constant would be true, if both arise from massive star formation and a constant, universal initial mass function. While this is probably the simplest assumption, other scenarios are possible. For example, if a first generation of HN associated with very massive stars (Population III) has existed, it could have produced proto-galactic beryllium, along with C and O. If these Pop III HNe produce strictly C and O but little or no iron, then this Be component would manifest itself under as a plateau in the Be-Fe correlation at the lowest metallicity (but a linear, primary trend in Be-O). Consequently, if this Be-Fe plateau were observed, it would not necessarily imply that BBN has contributed. In this scenario, the HN rate would not follow the SN rate during the Pop III phase. Thus, this picture could be tested by measuring the cosmic SN and HN rates at high redshifts.

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